

STATIC MAGNETIC FIELDS

INTRODUCTION

The fields associated with most magnets used at Fermilab are constrained to their interiors and hence do not present an exposure hazard. The notable exceptions are fields from analyzing magnets which are employed extensively in the fixed target research program. The static magnetic fields from these devices may be as high as several tesla and, though the intensity decreases rapidly with distance, may require many meters to drop to negligible levels. The hazards of exposure to static magnetic fields include forces on ferrous objects and interference with various medical devices (especially cardiac pacemakers and ferrous implants/prostheses). Other effects have not been shown to be harmful. This chapter describes procedures to control the hazards associated with exposure to static magnetic fields.

APPLICABLE STANDARDS

ACGIH Threshold Limit Values - Static Magnetic Fields

SPECIAL RESPONSIBILITIES

Persons controlling devices which produce magnetic fields in excess of those identified in (1.) and (2.) of the procedures section below are responsible for informing their division/section ES&H Group regarding the use of these devices. Most important are new applications or modifications which may result in increased exposures.

In addition to screening personnel for cardiac pacemakers, metallic implants, metallic prosthesis, medical electronic devices, or active sickle cell anemia, the Medical Office is responsible for informing such personnel about the hazards of exposure to static magnetic fields and notifying division/section ES&H groups regarding the presence of such personnel.

PROCEDURES

1. Exposure Limits - The exposure limits given below refer to static magnetic fields to which it is believed that nearly all workers may be repeatedly exposed without experiencing adverse health effects¹.

Target body area	Exposure limit		Time averaging
	(mT)	(G)	
Torso (cardiac pacemaker)	0.5	5	Ceiling
Torso or head ("whole body")	60	600	TWA
Extremities	600	6000	TWA
Any part of body	2000	20,000	Ceiling

2. Action Levels - Action levels are one-half of the personnel exposure limits given above.

Target body area	Action level		Time averaging	Hazard type
	(mT)	(G)		
Torso	0.25	2.5	Ceiling	Cardiac pacemaker
Torso or head	30	300	TWA	High magnetic field
Extremities	300	3000	TWA	High magnetic field
Any part of body	1000	10,000	Ceiling	High magnetic field

In low intensity magnetic fields the functioning of cardiac pacemakers and similar devices are the only concerns. In high intensity magnetic fields, forces on ferrous objects, interference with various other medical devices, and impaired circulation in persons with active sickle cell anemia become important.

3. Exposure assessment - The division/section controlling the magnetic field source shall assure that initial monitoring is conducted whenever an activity is reasonably expected to result in exposures exceeding one or more of the action levels. Limits in (1.) and (2.) above should only be applied to positions where occupancy by the applicable "target body area" is anticipated (*i.e.*, the "torso" limit should only be applied to locations where someone's torso is likely to be positioned). In addition, these limits have been set assuming a homogeneous field. For inhomogeneous fields, the average magnetic flux density should be measured over an area of 100 cm². This spatial averaging partially addresses concerns about regulating dimensionally small magnetic field sources.

If results do not exceed action levels, further monitoring is not required unless the activity is modified in a way which is expected to increase exposures. If

¹See the Technical Appendix to this Chapter for a discussion of health effects.

results are found to exceed action levels, periodic monitoring shall be conducted at a frequency which is sufficient to ensure the continued adequacy of control measures (usually no greater than annually).

4. Controls - The following control measures shall be implemented where static magnetic fields exceed action levels.

a. *Cardiac Pacemakers*

B_{ceiling} > 0.25 mT (2.5 G) @ torso

- i. Operations which may result in torso exposures exceeding 0.25 mT (2.5 G) shall be posted with cardiac pacemaker warning signs in a way which best serves to warn potentially exposed personnel. These signs are available from the ES&H Section (see below).



- ii. Persons with cardiac pacemakers shall be prohibited from the area unless formally permitted by the Occupational Medicine Director.

b. *High Magnetic Fields*

B_T W_A > 30 mT (300 G) @ torso

B_T W_A > 300 mT (3000 G) @ extremities

B_{ceiling} > 2000 mT (20,000G) @ any part of body

- i. High magnetic field signs shall be posted in a way which best serves to warn potentially exposed personnel. These signs are available from the ES&H Section (see below).



- ii.. Ferrous objects should be prohibited and shall at least be used in a fashion which prevents them from being a hazard. This includes safety shoes containing iron.

The extent to which magnetic forces present a safety hazard can, and should, be empirically verified. Translational forces appear to become a problem when the product of the magnetic field and its gradient is in the range of $100\text{-}1000 \text{ (mT)}^2/\text{m}$ ($100\text{-}1000 \text{ G}^2/\text{cm}$). Rotational forces appear to become a problem at a magnetic field strength of 60 mT (600 G).

- iii. Persons with metallic implants (excluding dental fillings), metallic prosthesis, medical electronic devices, or active sickle cell anemia shall be prohibited from the area unless formally permitted by the Occupational Medicine Director.

- 5. A technical appendix is attached which describes the bases for this ES&H Manual Chapter.

TECHNICAL APPENDIX TO STATIC MAGNETIC FIELDS (SAFETY NOTE #21)

This technical supplement describes the basis for the Fermilab ES&H Manual chapter on magnetic fields. In general, static magnetic fields interact only weakly with biological material and harmful effects must be mediated by ferrous objects.

1. Effects of Exposure

Below is a summary of information on the better understood effects of exposure to static magnetic fields.

a. *Cardiac Pacemaker Interference*

Cardiac pacemakers use magnetically activated reed switches to alter their operating mode. Normally, pacemakers sense and amplify the heart's natural pacing signal. In the alternate safety backup mode pulses are sent out at a fixed rate. The magnetic switch is provided to allow testing of the backup mode by holding a permanent magnet to the person's chest. In seriously ill individuals, the fixed frequency signal could destructively compete with the heart's natural pacing signal. Some pacemakers can be switched by magnetic fields as low as 1.4×10^{-3} T (=14 G) [Pa83]. At the time of this writing, there are very few individuals with cardiac pacemakers working at Fermilab.

b. *Magnetohydrodynamic Effects*

When an electrically conductive fluid flows in a magnetic field, an electric current is produced, as is a force opposing the flow. This occurs when blood flows through the vessels of a person exposed to a static magnetic field and the effects are greatest when flow is perpendicular to the field. The potential across such a vessel is

$$E = 0.1 B_0 v d,$$

Where E = potential across the vessel (mV)
 B_0 = magnetic flux density in the absence of the person (T)
 v = blood flow velocity (cm/s)
 d = blood vessel diameter (cm)

This potential is negligible in all but the largest arteries, i.e., the aorta and femoral artery, where values on the order of 5 mV/T can occur. On an electrocardiogram, this appears as an enhancement of the T-wave, though the sources of the potentials are unrelated. No harmful effect has been associated with this mechanism.

The force opposing flow appears as an increase in blood pressure [Ea82]:

$$\Delta BP = 3 \times 10^{-3} B_o^2$$

Where ΔBP = increase in blood pressure (mmHg)
 B_o = magnetic flux density in the absence of the person (T)

This relation predicts a negligible increase, requiring 18T to obtain 1 mmHg. There appears to be no reason to limit magnetic field exposures based on the consequences of magnetohydrodynamic effects.

c. *Other Physiological Effects*

Some other physiological effects which may have impact on occupational health include are summarized below from reference Si92.

Alignment of human sickled red blood cells occurs in fields >0.2 T. It is suspected that this may cause local circulatory reductions in small vessels at fields substantially greater than this value. However, brief (2 minute) *in vivo* exposures with resting subjects showed no adverse effects. However, this level of exposure would generally be controlled by following the controls for high magnetic fields. Therefore, persons with sickle cell anemia should be kept out of such areas.

Human subjects exposed to 1-2 T fields for 10 minutes showed an intensity-dependent decrease in heart rate (17% @ 2 T). No effect was seen at 0.23 T. Squirrel monkeys exposed to 7 T for at least 2 hours showed a slowing of the heart rate of about 25%. There does not appear to be any risk to healthy workers from this effect, but the safety of dysrhythmic personnel is uncertain.

There have been anecdotal reports of effects associated with head motion in 2-4 T fields. This includes visual disturbances ("phosphenes"), taste sensations, pain from fillings in teeth, vertigo, nausea, and headaches.

In general, occupational epidemiological studies of static magnetic fields have suffered from the possibility of confounding exposures that could

be responsible for observed effects. However, a few studies involving large numbers of workers exposed to 4-50 mT (40-500 G) fields in aluminum electrolysis processes have shown excess pancreatic cancer or leukemia deaths. The pancreatic cancer data showed a statistically-significant increase of 68% in workers exposed for at least five years. However, the death rate from all cancers was significantly less than that in the control population in this study. The leukemia study showed a statistically-significant increase of 90% in aluminum workers. However, the possible effect of confounding factors is unclear. Another study identified a dose-dependent decrease in white blood cell count for workers continuously exposed to horizontal fields up to 7 mT (70 G). The decrease was within the normal range of acceptable values.

d. *Magnetic Forces on Ferrous Objects*

Ferrous objects can experience rotational and translational forces when immersed in a magnetic field. These forces can increase the risk of accidents associated with the use of common work materials (such as tools, carts, gas cylinders, and safety shoes) as well as that of medical emergencies (such as the removal of aneurysm clips).

Rotational Force

The torque experienced by a ferrous object depends on the magnetic field strength:

$$L_{\text{mag}} = -mH \sin \theta$$

Where L_{mag} = torque experienced by the ferrous object (N-m)
 m = magnetic moment of the ferrous object (Wb-m)
 H = magnetic field density (A/m)
 θ = angle between the magnet moment and the field (°)

The following table summarizes observations made by T. Miller and J. Kenny in 1987 at the Fifteen Foot Bubble Chamber. These effects were observed using a wrench, nail, pen, clip board, safety shoes, and gaussmeter.

These results neatly match whole body exposure limits: some interference at the 30 mT (300 G) action level and significant interference at the 60 mT (600 G) personnel exposure limit.

Approximate field strength		Rotational force observation summary
mT	G	
< 6	< 60	No perceptible rotational force
~ 60	~ 600	Rotational force clearly interferes with use of ferrous objects
> 200	> 2000	Rotational force makes normal handling of ferrous objects almost impossible

Translational Force

The translational magnetic force can be calculated from the gradient of the change in the magnetic field energy density resulting from the presence of the ferrous object in the magnetic field.

$$\vec{F}_{\text{mag}} = \nabla[(U - U_0)V]$$

Where F_{mag} = magnetic force on the ferrous object (N)
 ∇ = gradient operator
 U = energy density with ferrous object (J/m³)
 U_0 = energy density without ferrous object (J/m³)
 V = volume of ferrous object (m³)

The magnetic field energy density is given by:

$$U = \frac{1}{2} \vec{B} \cdot \vec{H}.$$

Where B = magnetic flux density (T)
 H = magnetic field density (A/m)

The magnetic flux density in the absence of the ferrous object is

$$\vec{B}_0 = \mu_0 \vec{H}.$$

Where μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m

If it is assumed that the ferrous object is spherical (since other geometries are incredibly complicated), the internal magnetic flux density is [P178]:

$$\vec{B} \approx 3\mu_0 \vec{H}.$$

Therefore, the magnetic force is approximately

$$\mathbf{F}_{\text{mag}} = \nabla \left\{ \left[\frac{1}{2} (3\mathbf{m}_0 \mathbf{H} \cdot \mathbf{H}) - \frac{1}{2} (\mathbf{m}_0 \mathbf{H} \cdot \mathbf{H}) \right] V \right\}$$

$$\mathbf{F}_{\text{mag}} = \nabla (\mathbf{m}_0 H^2 V) = \nabla \left(\frac{V}{\mathbf{m}_0} B_0^2 \right)$$

$$F_{\text{mag}} = \frac{2V}{\mathbf{m}_0} B_0 \frac{dB_0}{dr}$$

It is now possible to determine the field conditions which result in the translational magnetic force that can be expected to interfere with normal handling. We will assume this occurs when the translational force is equal to one-tenth the force due to gravity. In addition, we will assume that the object is an iron sphere.

$$F_{\text{mag}} = 0.1 F_{\text{grav}}$$

$$\frac{2V}{\mathbf{m}_0} B_0 \frac{dB_0}{dr} = 0.1 r V g$$

$$B_0 \frac{dB_0}{dr} = \frac{0.1 \mathbf{m}_0 r g}{2} = \frac{(0.1)(4\pi \times 10^{-7} \frac{\text{H}}{\text{m}})(7900 \frac{\text{kg}}{\text{m}^3})(9.8 \frac{\text{m}}{\text{s}^2})}{2}$$

$$B_0 \frac{dB_0}{dr} = 4.9 \times 10^{-3} \frac{\text{T}^2}{\text{m}} (= 4.9 \times 10^3 \frac{\text{G}^2}{\text{cm}})$$

Limited measurements made in 1987 *suggest* that translational forces may be "noticeable" above $10^{-4} \text{ T}^2/\text{m}$ ($10^2 \text{ G}^2/\text{cm}$) and equal to the gravitational force above $10^{-3} \text{ T}^2/\text{m}$ ($10^3 \text{ G}^2/\text{cm}$). However, a subset of the observations indicate that much higher values - up to 100X - are needed to produce problematical translational forces.

2. Exposure Limits

DOE Order 5480.4 indicates that the American Conference of Governmental Industrial Hygienists Threshold Limit Values is a mandatory standard. The most current version of the TLVs contains the following statement for static magnetic fields [ACGIH94]:

"These TLVs refer to static magnetic flux densities to which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects. These values should be used as guides in the control of exposure to static magnetic fields and should not be regarded as a fine line between safe and dangerous levels.

Routine occupational exposures should not exceed 60 milliteslas (mT) - equivalent to 600 Gauss - whole body or 600 mT (6000 Gauss) to the extremities on a daily, time-weighted average basis. A flux density of 2 Teslas is recommended as a ceiling value. Safety hazards may exist from the mechanical forces exerted by the magnetic field upon ferromagnetic tools and medical implants. Workers having implanted cardiac pacemakers and similar medical assist devices should not be exposed above 1.0 mT (10 Gauss). Perceptible or adverse effects may also be produced at higher flux densities resulting from forces upon other implanted ferromagnetic devices, e.g., suture staples, aneurism clips, prostheses, etc."

There is also a notice of intended changes included with this standard which reduces the limit for cardiac pacemakers from 1.0 mT (10 Gauss) to 0.5 mT (5 Gauss). This change may be proposed to bring the standard in line with accepted hospital posting practices around magnetic resonance machines [An86]. The lower value has been adopted by Fermilab since it appears to be the generally-accepted limit and it is likely that it will be adopted by the ACGIH.

The personnel exposure limits given in Chapter 5062.2 are a synopsis of the TLV for static magnetic fields, including the proposed lower limit for cardiac pacemakers. It should be noted that these are exposure limits and not emission limits. Therefore, they cannot be trivially expressed as a magnetic flux density at a fixed distance from a field source. Exposures must be assessed at the positions where occupancy by the applicable "target body area" is anticipated. For purposes of exposure evaluation, "extremities" is taken to include arms, hands, fingers, legs, feet, and toes. "Whole body" is taken to mean the torso and head, but not extremities, which have a greater exposure limit. The "ceiling" limit appears to apply to any part of the body (*i.e.*, torso, head, arms, hands, fingers, legs, feet, or toes). The "cardiac pacemaker" limit should be evaluated based on anticipated torso location, not on that of the head or extremities.

3. Actions Levels

Recognizing that exposure monitoring is generally intermittent and work processes vary, it is prudent to establish action levels, below actual exposure limits, which trigger implementation of control measures. It is common practice in industrial hygiene to use one-half of exposure limits for this purpose and this approach has been generally adopted by OSHA in the majority of its industrial hygiene work practice standards.

The action levels given in Chapter 5062.2 are one-half of the personnel exposure limits.

4. Exposure assessment

Monitoring for static magnetic fields should be conducted whenever there is a reasonable likelihood that an action level will be exceeded. A "yes" answer to any of the following questions should trigger monitoring.

- a. Is this a new/modified static magnetic field producing device for which it is uncertain whether exposures will be within action levels?
- b. Can torso exposures exceed 0.25 mT (2.5 G)?
- c. Can head exposures exceed 30 mT (300 G)?
- d. Can extremity exposures exceed 300 mT (3000 G)?
- e. Are there apparent magnetic forces on ferrous objects?
- f. Will a person with a cardiac pacemaker be working in the area?

The magnetic field exposure limits and action levels limit personnel exposure, not field emission. Therefore, they should only be applied to positions where occupancy by the applicable "target body area" is anticipated (*i.e.*, the "torso" limit should only be applied to locations where someone's torso is likely to be positioned). In addition, these limits have been set assuming a homogeneous field. For inhomogeneous fields, the average magnetic flux density should be measured over an area of 100 cm². This spatial averaging has been proposed by the International Commission on Non-ionizing Radiation Protection (IC94). Although not as simple as specifying a magnetic flux density limit at a fixed distance from a source, it does partially address concerns about regulating dimensionally small magnetic field sources.

The need for and frequency of periodic monitoring should be tied to the likelihood that control measures may not remain adequate. If initial monitoring indicates that exposures are below action levels, then additional monitoring is not required, unless the equipment or operation is modified in a way which is likely to increase exposures. This philosophy is consonant with

current industrial hygiene practice and mimics that employed in OSHA work practice standards.

The ES&H Section has instrumentation and procedures for making such measurements. This organization will also conduct monitoring as part of routine monitoring and in response to requests.

5. Controls

In general, the bases for the control measures are obvious and their implementation is straightforward. Below is clarification of a few aspects which may be unclear.

a. *Cardiac Pacemakers*

The Occupational Medicine Director may allow persons with cardiac pacemakers to work in static magnetic fields exceeding 0.25 mT (2.5 G). This decision would presumably be based on more complete information about the susceptibility of the worker's device/condition (such as from experience, manufacturer information, or input from the worker's personal physician). Most pacemakers require somewhat higher fields to change operating states - some up to ~5 mT (50 G) [Pe89]. In addition, some pacemaker wearers are not necessarily placed at grave risk subsequent to a change in operating states.

b. *High Magnetic Fields*

These fields may produce forces on ferrous objects as well as potentially harmful physiological effects. As with cardiac pacemakers, the Occupational Medicine Director may allow persons with metallic implants, metallic prosthesis, medical electronic devices, or active sickle cell anemia to work in these fields. This decision would presumably be based on more complete information about the susceptibility of the worker's device/condition (such as from experience, manufacturer information, or input from the worker's personal physician).

References

- ACGIH 93 American Conference of Governmental Industrial Hygienists, 1993, *1993-1994 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices* (Cincinnati, OH: ACGIH).
- An86 Anderson D., Yamanashi W., Lester P. and Gilmore R., 1986, "Ferromagnetic screening around a superconducting magnetic resonance imager," *Health Physics* **51**, 545.
- Bu81 Budinger T., 1981, "Nuclear magnetic resonance (NMR) *in vivo* studies: known thresholds for health effects," *J. Comput. Assist. Tomogr.* **5**, 800.
- Ea82 Easterly C., 1982, "Cardiovascular risk from exposure to static magnetic fields," *Am. Ind. Hyg. Assoc. J.* **43**, 533.
- IC94 International Commission on Non-ionizing Radiation Protection, 1994, "Guidelines on limits of exposure to static magnetic fields," *Health Physics* **66**, 100.
- Pa83 Pavlicek W, Geisinger M., Castle L., Borkowski G., Meaney T., Bream B. and Gallagher J., 1983, "The effects of nuclear magnetic resonance on patients with cardiac pacemakers," *Radiology* **147**, 149.
- Pe89 Persson B. and Stahlberg F., 1989, *Health and Safety of Clinical NMR Examinations* (Boca Raton, FL: CRC Press).
- Pl78 Plonus M., 1978, *Applied Electromagnetics* (New York: McGraw Hill).
- Si92 Simon N., 1992, *Biological Effects of Static Magnetic Fields* (Boca Raton, FL: CRC Press).

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